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Annual Thermodynamic Analysis of Solar Power with Steam Injection Gas Turbine (STIG) Cycle for Indian Conditions

A. Immanuel Selwynraj[a], S.Iniyan[b]*, L.Suganthi[c], M.Livshits[d], Guy Polonsky[d], Abraham Kribus[d]

[a,b]*Dept of Mechanical Engineering,* [c]*Dept of Management Studies*
Anna University, Chennai 600 025, Tamilnadu, India
[d]*School of Mechanical Engineering, Tel Aviv University, Tel Aviv 69978, Israel*

Abstract

Solar thermal energy is now being widely utilized to meet the world's energy demand due to its huge potential. Power generation from solar is varying and high cost of solar thermal energy systems that makes sense only in regions with high solar insolation. In order to overcome these practical issues, low cost solar hybrid steam injection gas turbine (STIG) cycle is adapted. Both gas turbine exhaust stream and solar heat are used for steam generation, and then it is injected into the combustor. The steam injection reduces NO_X and CO_2 emission in addition to increased power output and plant efficiency compared to the simple cycle. It offers a path for high conversion efficiency without the requirement of operating at high temperature and high pressure in the solar components. The objective of the proposed work is to investigate a conversion method for solar radiation that offers potentially high conversion efficiency and for increased competitiveness against fossil fuels. The annual performance of the cycle for sites in India with local climatic conditions such as ambient temperature, relative humidity and availability of direct normal irradiance to the solar concentrators under two modes of constant and variable power is presented in this paper. The results reveal that the solar to electricity efficiency of solar hybrid STIG plant with a simple Parabolic Trough Collector (PTC) is similar to existing solar thermal technologies and higher solar share is obtained. The study also reveals that the annual CO_2 emission is similar to combined cycle plants and lower than gas turbine technologies.

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Keywords: steam injection; solar hybrid STIG cycle; gas turbine cycle;

* Corresponding author. S.Iniyan Tel.: +044-22357601; fax: +044-22357600.
E-mail address: iniyan@annauniv.edu, iniyan777@hotmail.com.

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1. Introduction

Gas turbine has become the premier electric generation system for peak and base loads to meet the future demand using both high and low heat content fuels, with low emissions. Natural gas is the least carbon intensive fossil fuel, which is one of the major fuels used in the electric sector. The natural gas reserves in India as on March 2012 are 1330.26 billion cubic meters [1] and more scope to enhance the power generation through gas fired power plant. As on February 2013, the installed capacity of gas based power plant in India is 19,648.85 MW, about 9.15% of the India's total installed capacity [2].

Nomenclature

I	Direct normal insolation (DNI) W/m^2
LHV	Lower Heating Value kJ/kg
$\dot{m}$	Mass flow rate kg/s
q	Specific heat input kJ/kg-air
SAR	Steam to air ratio kg-steam/kg-air
SF	Solar fraction
T	Temperature ^{o}C, K
w	Specific work kJ/kg-air
y	Mass fraction
η	Efficiency

Sub- and super-scripts

a	Ambient
c	Collector
C	Compressor
d	Condenser
f	Fuel
inc	Incremental
n	Net
p	Pump
ref	Reference
s	Solar
t	Turbine

India is endowed with rich solar energy resource. There are about 300 clear sunny days in a year in most parts of India and the daily average solar energy incident over India varies from 4-7 kWh/m^2 [3].The performance of gas turbine plant mainly depends on ambient conditions of air. Steam injection

into the gas turbine (STIG) can increase the performance of the gas turbine and the improvement in the power output is based on the increased mass flow through the turbine when compared with the compressor mass flow. This causes power augmentation and an increase in efficiency compared to the simple cycle [4]. In principle, recovery of the turbine exhaust energy in a combined cycle arrangement can lead to even higher efficiency, but for moderate power level, STIG performance can be better than combined cycle [5]. The hybridization of solar STIG cycle [6] leads to overcoming intermittency of solar power and cost issues. Presently, steam is injected into or around the fuel nozzles to reduce the NO_x levels [7]. In the solar hybrid STIG, the irreversibility is minimized by assigning the gas turbine exhaust primarily to the superheat and economizer sections, while solar heat input is best used for evaporation, as shown in Fig. 1. The solar collectors for the STIG cycle are required for evaporation only at moderate temperatures around 200°C, at a low pressure matching the Gas Turbine pressure [6]. This can be implemented with inexpensive collectors such as a simplified version of a parabolic trough or a linear Fresnel. In the previous studies, nominal performance analysis of solar hybrid steam injection gas turbine cycle for varying pressure ratio and turbine inlet temperature was performed by using single set of ambient conditions [6]. A previous annual performance study has been investigated for two sites in Israel [10]. In the present work, the annual performance of the cycle is analyzed for two sites in India with detailed information on local climate at each site: ambient temperature and pressure (inlet conditions to the compressor), and availability of direct sunlight to the solar concentrators. A large share of these emissions in India is produced by the electricity and heat sector is, 54% of CO_2 in 2010 [8]. The annual variation of specific CO_2 emission is also presented in this paper for Indian conditions.

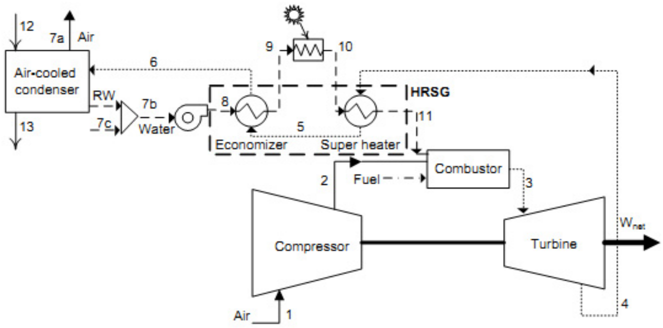


Fig. 1 Layout of Solar STIG cycle [11]

2. Methodology

A detailed thermodynamic simulations of the cycle were carried out based on the availability of solar radiation and ambient conditions for two sites in India, including realistic models of all main components (compressor, combustor, turbines, heat exchangers, pump, etc) using Honeywell Unisim process simulation software. The simulation method is described in [6] and [11]. The mass flow rate of air through the compressor was fixed as 1 kg/s. Steam injection into combustor increases the power output of a gas turbine by increasing the mass flow of 1+f+SAR kg/s through the turbine, relative to the compressor, without significantly increasing the power required to drive the compressor.

The annual thermodynamic simulations were carried out for a model based on the GE LM2000 gas turbine, with turbine inlet temperature (TIT) of 1100°C (1121°C for the real turbine), and a compressor pressure ratio (PR) of 15 (15.6 for the real turbine). The nominal power output of the cycle is 17.56 MWe, and the simple cycle efficiency is 35.5%. (based on LHV) [6]. Other parameters used in the simulation are presented in Table 1.

Table. 1. Input to the component models used in the simulation [6]

Parameter	value
Turbine isentropic efficiency	90%
Compressor isentropic efficiency	85%
Water pump isentropic efficiency	80%
Pressure drop in heat exchangers (except Condenser)	3%
Pressure drop in Combustor	4%
Minimum approach for the HRSG	10°C
Minimum approach for the condenser	15°C

3. System performance metrics

For solar hybrid STIG cycle, performance measures [9] were computed from the results of the simulation. The net specific work and the overall cycle efficiency (heat to work) are defined as:

$$W_n = W_t - W_c - W_p - W_d \tag{1}$$

$$\eta = \frac{W_n}{q_f + q_s} \tag{2}$$

W_t is the specific work output of the turbine; and W_c, W_p and W_d are the specific work inputs of the compressor, water pump and condenser, respectively. q_f and q_s are the specific inputs of heat per unit mass of air in the cycle from combustion of fuel and from the solar collectors, respectively.

Another performance measure of a hybrid cycle besides the cycle efficiency is the incremental solar efficiency which is defined as

$$\eta_{inc} = \frac{W_n - \eta_{ref} * q_f}{q_s} \tag{3}$$

η_{ref} is the overall net electricity efficiency of a reference fuel-only plant. For this work, the reference plant is selected as the same STIG plant operating at the maximum conventional steam injection rate without the addition of solar heat.

A commonly used performance measure to characterize hybrid cycle is the solar fraction or solar share. It is a fraction of heat from solar energy.

$$SF = \frac{q_s}{q_s + q_f} \tag{4}$$

The empirical equation for efficiency of a low temperature parabolic trough collector [10],

$$\eta_c = 0.7625 - 6.85 * 10^{-5} * (T_c - T_a) - 0.146 * \frac{T_c - T_a}{I} - 1.672 * 10^{-3} * \frac{(T_c - T_a)^2}{I} \tag{5}$$

The solar to electricity efficiency is based on incremental efficiency and solar collector efficiency.

$$\eta_s = \eta_{inc} * \eta_c \tag{6}$$

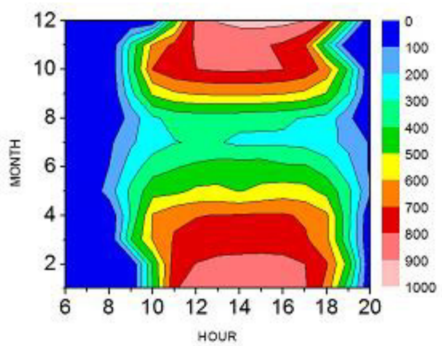
The specific CO_2 emission per unit of produced power is computed using the equation.

$$(Co_2)_{eq} = \frac{\dot{m}_{7a} * y_{co_2}}{W_n} \tag{7}$$

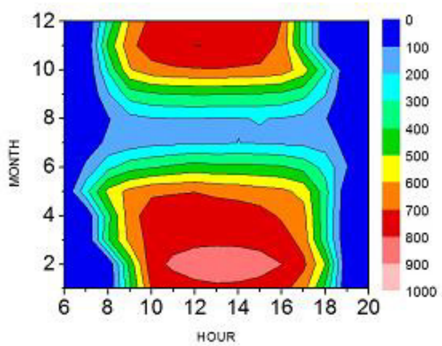
y_{co2} is the mass fraction of condenser exhaust gas. Similarly, from the results of simulation, the annualized performance measures such as annual solar to electricity efficiency, annual SF and annual specific CO_2 emissions were computed by average over the year for both constant and variable power scenario.

4. Annual Solar STIG cycle simulation

In the annual simulation, the simulation inputs are varied over the year. The annual simulation was performed for two sites in India: Jaipur (annual DNI=2180 kWh/m^{2}yr) and Indore (annual DNI=2061 kWh/m^{2}yr). Hourly data for a typical year was obtained from the Meteonorm software. The data includes ambient air temperature, relative humidity and direct solar radiation. The simulation was performed for a typical day in each month. For each site, hourly data for a representative clear day for each month was generated. Daily values of electricity output and heat inputs were obtained by an integral of the simulation results over the time interval during each day when the DNI exceeds 130 W/m^2 [11]. Annual values were obtained by summation of all representative days, weighted by number of days in each month, and a clearness index for the month.



(a) Jaipur



(b) Indore

Fig. 2. Annual distribution of DNI in W/m^2 for Jaipur and Indore

The annual distribution of DNI for Jaipur and Indore are shown in Figure 2. Though Jaipur has higher DNI, the DNI distribution in Indore is more uniform than Jaipur. Generally many parts of India have lower DNI during the months of June, July and August due to summer monsoons. Highest DNI values are recorded during beginning and end of the year.

4.1. Constant power scenario

In the constant power scenario, the power output of the cycle remains constant, even though the solar radiation varies. This scenario is suitable for applications requiring constant power output. Duct firing was added to supply additional heat in the HRSG, keeping the amount of injected steam constant regardless of the solar conditions, thus maintaining constant power output of the cycle.

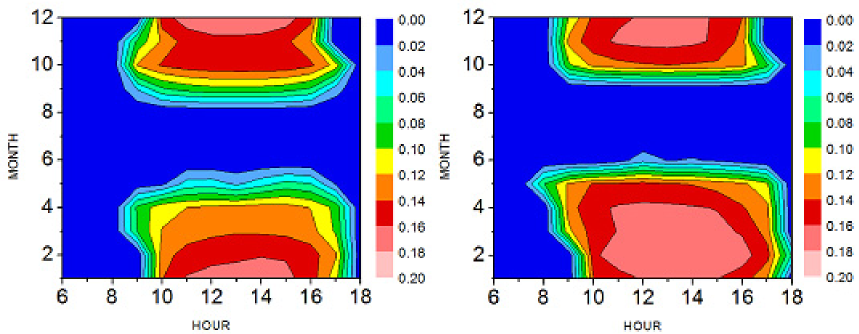
4.2. Variable power scenario

In the variable power scenario, the power output of the cycle varies to follow the solar radiation. This scenario is suitable for feeding into a large grid that is not significantly affected by this plant. The overall efficiency of the cycle might decrease slightly due to constant turbine isentropic efficiency in part-load operation of the turbine.

5. Annual performance results

5.1. Constant power results

Figure 3 shows that annual variation of solar to electricity efficiency at Jaipur and Indore for SAR = 0.7 in constant power scenario. The Table 2 results show that when SAR increases the peak and annual values of solar to electricity efficiency slightly decreases but solar fraction increases corresponding to an increase in solar heat. The reduction in solar efficiency is due to the increased fuel consumption both in the combustor for maintaining constant TIT when SAR increases, and in the HRSG through duct firing when solar heat availability is low. The annual solar-to-electricity efficiency ranges from 11.5% to 13.7% and the annual SF in the range of 7.19% - 27.3%, for the range of SAR shown in Table 2. The variation of annual solar-to-electricity efficiency for Indore is 4.58%, which is lower than



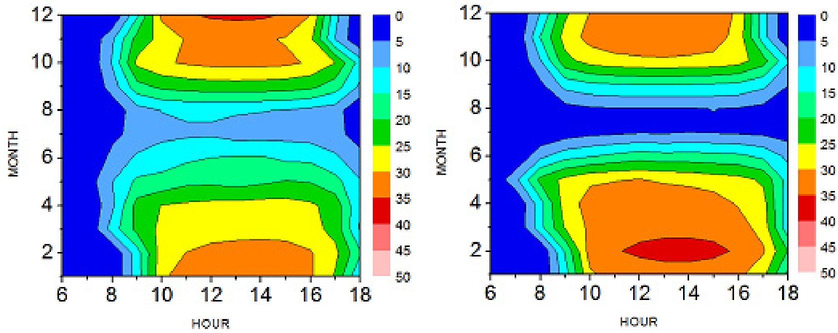
(a) Jaipur (b) Indore

Figure. 3. Annual variation of solar to electricity efficiency, constant power scenario, for SAR= 0.7

Table. 2. Peak and annual results for constant power at Jaipur and Indore for different SAR values

SAR	Jaipur				Indore			
	Solar to electricity efficiency, %		Solar Fraction, %		Solar to electricity efficiency, %		Solar Fraction, %	
	Peak	Annual	Peak	Annual	Peak	Annual	Peak	Annual
0.3	19.2	12.9	12.9	7.2	19.1	13.7	13.1	7.7
0.5	18.6	12.6	27.3	15.2	18.5	13.3	27.6	16.2
0.7	17.7	11.7	36.0	20.1	17.6	13.3	36.2	21.3
0.9	17.4	11.6	41.3	23.0	17.3	13.1	41.5	24.4
1.2	17.2	11.5	46.2	25.7	17.1	13.1	46.4	27.3

Jaipur having 12.17%. The annual variations of SF at both sites are shown in Figure 4. The results from the Table 2 show that the annual SF for various SAR values at Indore is about 6.43% higher than Jaipur. This percentage variation of annual solar to electricity efficiency and annual SF show that DNI distribution pattern for Indore is appreciable than Jaipur.

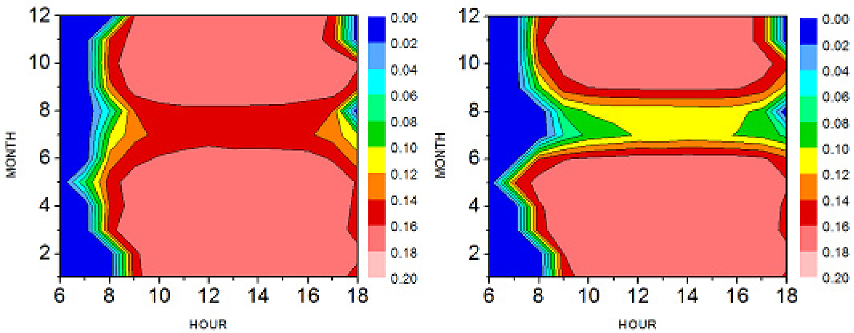


(a) Jaipur (b) Indore

Figure. 4. Annual variation of SF, constant power scenario, for SAR= 0.7 at Jaipur, Indore

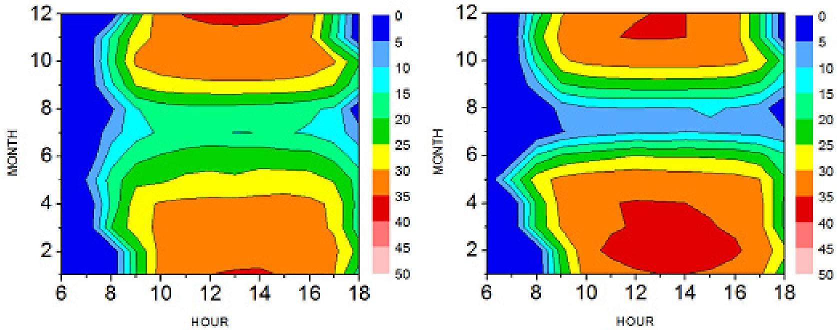
5.2. Variable power Results

The annual variation of Solar to electricity efficiency and annual SF at Jaipur and Indore for variable power scenario are shown in Figure 5 and Figure 6 respectively. In the variable power scenario, actual SAR varies with time based on solar heat availablity. The results from the Table 3 show that the variation of solar to electricity efficiency is slightly lower than peak values but higher than values corresponding constant power scenario since constant turbine isentropic efficiency is maintained. Similarly, the annual SF is higher than constant power scenario. This is because only the solar heat is used in the evaporation process. The annual solar to electricity efficiency ranges from 15.1% to 17% and the annual SF in the range of 7.78% - 35.87%. In this case, the percentage variation of annual solar to electricity for Jaipur is about 8% which is almost similar to Indore and the annual solar to electricity efficiency for various SAR values at Jaipur is about 4.7% higher than Indore. The annual SF for various SAR values at Jaipur and Indore are almost similar.



(a) Jaipur (b) Indore

Figure. 5. Annual variation of solar to electricity efficiency, variable power scenario, for SAR = 0.7



(a) Jaipur (b) Indore

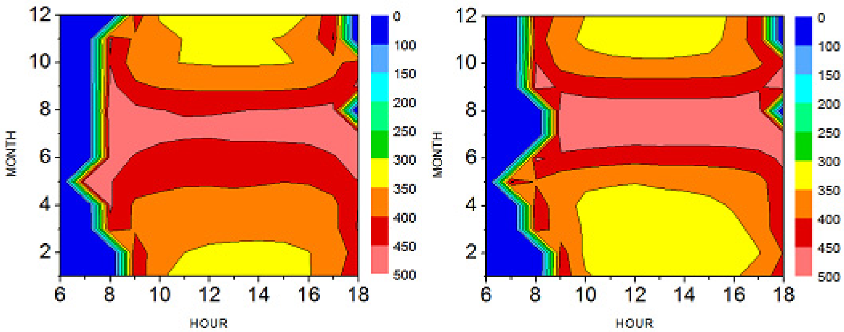
Figure. 6. Annual variation of SF, variable power scenario, for SAR = 0.7 at Jaipur and Indore

Table. 3. Peak and annual results for variable power at Jaipur and Indore for several SAR values

SAR	Jaipur				Indore			
	Solar to electricity efficiency, %		Solar Fraction, %		Solar to electricity efficiency, %		Solar Fraction, %	
	Peak	Annual	Peak	Annual	Peak	Annual	Peak	Annual
0.3	19.2	17	12.9	7.8	19.1	16.3	13.1	8.2
0.5	18.6	17	27.3	18.1	18.5	16.2	27.6	18.6
0.7	17.7	16.4	36.0	25.5	17.6	15.7	36.2	25.8
0.9	17.4	16.2	41.3	30.5	17.3	15.3	41.5	30.7
1.2	17.2	15.7	46.2	35.9	17.1	15.1	46.4	35.8

5.3. Specific CO_2 emission results

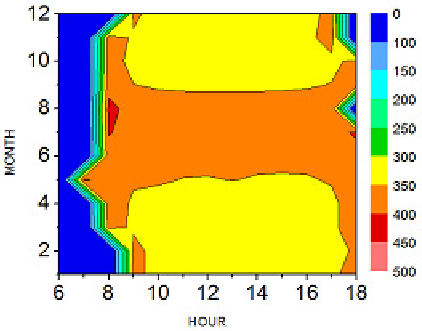
The annual specific CO_2 emission equivalent of the solar STIG cycle with methane fuel for SAR = 0.7 of both constant and variable power scenarios are shown in Figure 7 and Figure 8 respectively. The emission of CO_2 is considerably reduced by injecting more amount of steam into the combustor.



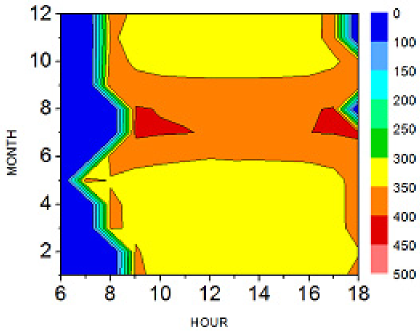
(a) Jaipur (b) Indore

Figure. 7. Annual variation of specific CO_2 emission in kg/MWh, constant power scenario, SAR=0.7

In the variable power scenario, available solar heat is utilized and there is no excess fuel consumption. In order to maintain constant power, the fuel fraction increases significantly when solar radiation is low which leads to higher specific CO_2 emissions than in the variable power scenario. The results from the Table 4 show that when SAR increases, specific CO_2 emission gradually decreases for both scenarios and the percentage variation of annual specific CO_2 emission equivalent for the variable power scenario is 2.5-24% lower than constant power scenario. The range of annual specific CO_2 emission is 319-413 kg/MWh, which is close to the specific emissions of combined cycle power plants, and lower than conventional gas turbine and steam cycle plants. The specific CO_2 emission equivalent for the variable power scenario and constant power scenario for both Jaipur and Indore are almost similar.



(a) Jaipur



(b) Indore

Figure. 8. Annual variation of specific CO_2 emission in kg/MWh, variable power scenario, SAR=0.7

Table. 4. Peak and annual results of the specific CO_2 emission

SAR	Constant power scenario				Variable power scenario			
	Jaipur		Indore		Jaipur		Indore	
	Peak	Annual	Peak	Annual	Peak	Annual	Peak	Annual
0.3	387.6	413.4	387.4	411.1	387.6	402.3	387.4	401.2
0.5	345.5	403.5	345.0	398.7	345.5	372.1	345.0	370.7
0.7	320.4	400.9	319.9	394.4	320.4	351.2	319.9	350.1
0.9	303.7	398.9	303.1	391.3	303.7	336.0	303.1	335.4
1.2	286.8	396.6	286.3	388.0	286.8	319.8	286.3	319.5

6. Discussions and Conclusions

The annual performance of the solar hybrid STIG cycle using meteorological data for Jaipur and Indore is presented. The annual solar to electricity efficiency ranges between 11.5-13.7% for constant power scenario and 15.1-17% for variable power scenario when the solar collectors in the solar STIG plant operating steam conditions are at 16 bar and 200°C. This is similar to annual solar to electricity efficiency of low cost collectors used in solar thermal power plant such as parabolic trough collector and slightly higher than linear Fresnel plants, while the operating steam conditions at 390°C and 50-100 bar [12]. Moreover, PTC and LFC solar plants having such operating steam pressure and temperature require larger collector area and high cost.

The annual solar fraction ranges between 7.19-27.3% for constant power scenario and 7.78-35.87% for variable power scenario for various SAR values. These annual SF values are comparable with PTC and LFC solar plants having annual solar capacity factor (solar fraction in case of hybrid plant) 22-24% while the operating steam conditions at 390°C and 50-100 bar [12] and higher than the integrated solar combined cycle (ISCC), having less than 10% on base load operation [13], but it can reach the limit of 15% in summer [14]. Higher the solar fraction leads to significant reductions in the fuel consumption and CO_2 emissions.The integration of thermal energy storage will enhance the solar fraction and operating the plant beyond sunshine hours need to be studied.

The range of annual specific CO_2 emission is 387-413 kg/MWh for constant power scenario and 319-402 kg/MWh for variable power scenario for various SAR values. The annual specific CO_2 emission is comparable to ISCC with annual specific CO_2 emission of 368-380 g/kWh [15]. The annual specific CO_2 emission is lower than the natural gas combined cycle (NGCC) with an annual specific CO_2 emission of 357-440 g/kWh [16,17]. The specific CO_2 emissions are lower than the gas turbine technology of about 540 g/kWh [18]. The economic analysis of solar STIG plant for Jaipur and Indore requires further study and comparable with other solar thermal based plants.

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